Dynamic Analysis of the AFCI Scenarios

A. M. Yacout, R. N. Hill, L. Van Den Durpel, and P. J. Finck
Argonne National Laboratory
9700 S. Cass Ave.
Argonne, IL 60439
yacout@anl.gov

E. A. Schneider and C. G. Bathke
Los Alamos National Laboratory
P. O. Box 1663, Los Alamos, NM 87545, USA
eschneider@lanl.gov

J. S. Herring
Idaho National Engineering and Environmental Laboratory (INEEL)
P.O. Box 1625, Mail Stop 3605
Idaho Falls, ID 83415-3605
sth@inel.gov

Abstract – This work describes the dynamic analysis of different Advanced Fuel Cycle Initiative (AFCI) scenarios that aim at exploring the potential of using advanced nuclear energy systems to reduce the difficulties associated with the disposition of nuclear spent fuel. Different reactor deployment strategies have been considered including once-thru, single-recycle, and multiple-recycling scenarios, and its combinations. The impact of those strategies on repository performance has been investigated through the estimation of the waste heat load associated with each scenario. Conclusions regarding the impact of the different scenarios are presented

1. INTRODUCTION

The Advanced Fuel Cycle Initiative (AFCI) is a part of the DOE's integrated nuclear research approach that address the numerous issues facing the future of nuclear energy.[1] The initiative addresses both intermediate and long term issues associated with managing the spent nuclear fuel. The intermediate-term issues include the reduction of the spent nuclear fuel volumes and improving the geologic repository performance while recovering the energy contained in that fuel. The long-term issues are related to the reduction of the spent fuel radiotoxicity and long-term heat load, in addition to supporting the development of potential Generation IV fuel cycles.

Previous system studies [2] identified promising fuel cycle options for waste transmutation and provided self consistent evaluations of their performance. The current study presents some of those options in the framework of the AFCI and the implications of corresponding deployment scenarios on spent nuclear fuel management. The dynamic analyses of those scenarios show that significant reduction in key repository performance parameters can be achieved. The analyses also show that delays in implementing the scenarios can have significant consequences regarding the waste management issues.

2. PROPOSED SCENARIOS

Each of the scenarios proposed here starts with the existing US park of nuclear reactors (BWRs and PWRs) based on the DOE/EIA information.[3] Then the nuclear capacity is assumed to remain at the current level throughout the simulation; (modest growth scenarios have also been considered, but are not the focus of this paper). Maintaining this level of nuclear capacity throughout the century is accomplished in the different scenarios using different strategies to replace the plants that are removed from service. Those scenarios are once-thru LWR with spent fuel separation only, single MOX recycle, and single and double tier transmutations systems.

In the above scenarios, the plutonium and neptunium (Pu+Np) are separated from the once-thru LWR spent fuel and recycled back into MOX fuel. The advanced LWR (ALWR) MOX transmutation systems are deployed according to the availability of Pu+Np; otherwise once-thru ALWR systems are deployed to achieve the targeted power production. The double tier transmutation systems consisted of an initial MOX fuel pass in a thermal transmutation system followed by repeated transuranic recycle in a fast transmutation system.

General scenarios data and assumptions are as follows. The reprocessing capacities associated with the different scenarios ranged from 2,000-3,000 MT/yr for the no-growth scenario, and 2000-4,500 MT/yr for the modest growth scenario. The spent fuel cooling periods before reprocessing are assumed to be 5 years for the LWR and LWR-MOX spent fuel, and 3 years for the FR spent fuel. Finally, the reprocessing losses (for all types of reprocessing) are assumed to be 0.2%.

3. DYNAMIC ANALYSIS OF THE FUEL CYCLE PERFORMANCE

A number of objectives have motivated this analysis effort. Those objectives include the framing of quantitative goals for AFCI, highlighting the urgency of the waste management issues, and comparing diverse fuel cycle scenarios. The scenarios considered here include once-thru and separations only, single MOX recycle, and single and double tier transmutations systems. Both stable and growth scenarios were considered here, although most of the presented results correspond to the stable capacity scenario (0% growth of nuclear energy demand).

The results presented here were calculated using the nuclear energy systems dynamics analysis codes DYMOND and DANESS [4,5] and verified in part by the NFCSIM [6] code. The code simulates the energy-demand driven nuclear energy system scenarios over time and allows the simulation of changing nuclear reactor parks and fuel cycle options. The mass flows of the different fuel cycle spent fuel streams are followed and the associated decay heat generations are calculated. The calculations were performed for fast transmutation systems with 0.25 and 0 conversion ratio (the results for CR=0.25 system are presented here). Most of the attributes for the nuclear systems used in this study are published in references 2, 7, and 8.

The following sections describe the results of the analysis starting with a description of the growing LWR spent fuel inventory, followed by the impact of recycling on that inventory and the associated key radioactive species. The impact of recycle on repository is assessed by considering the decay heat associated with the different scenarios.

3.1 Growing Inventory of LWR Spent Fuel

Figure 1 shows the growth of the LWR spent fuel inventory under different growth rate scenarios and burnups. In those scenarios, the spent nuclear fuel (SNF) inventory grows significantly and exceeds Yucca Mountain repository loading (~ 65,000 MT initial HM) roughly by the year 2010. For the no-growth scenario, the SNF inventory increases by a factor of 4 from 2010 to 2100. With modest (1.5%) growth a factor of 7 increase is expected. As shown in the figure, improving the LWR burnup (from 50,000 to 60,000 MWd/t) can somewhat mitigate the buildup and reduce it to a factor of 6.

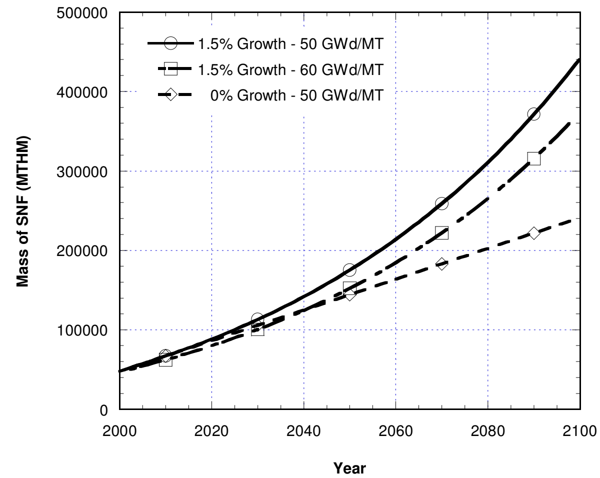

Fig. 1. LWR Spent Fuel Inventory at Different Growth Rates and Burnups.

3.2 Impact of Recycle on the LWR Spent Fuel Inventory

Recycle can significantly reduce the mass of SNF primarily by removal of uranium which is processed into low level waste. Figure 2 shows the mass of SNF associated with the different no-growth scenarios where the "Once-thru & Reproc." scenario corresponds to the case of LWR accompanied by SNF separation.

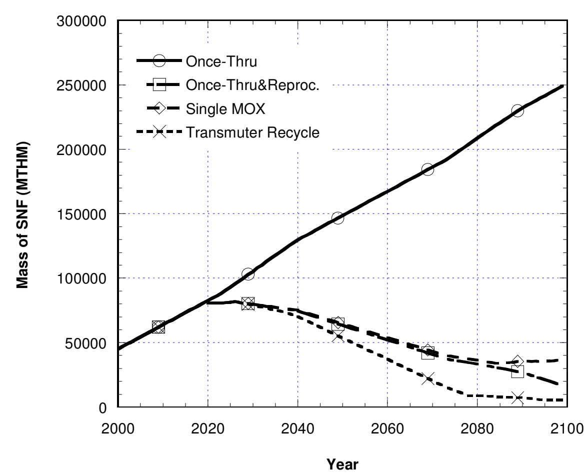

Fig. 2. Spent Fuel Inventory for the Different No-Growth Scenarios

Significant mass reduction is shown for the case of separation only. In the long run, single MOX recycle can reduce mass by a factor of 5. Further reduction can be achieved through a multi-recycle scenario that includes transmuter systems.

3.3 Dependence of the Deployment of Fast Transmuters on Reprocessing Capacity

Figure 3 shows an example of a possible fast transmuter system deployment as a fraction of the total nuclear capacity. In this scenario the growth rate is zero and the LWR spent fuel reprocessing capacity is 2,000 MT/yr starting 2020. In this fixed nuclear capacity scenario the deployed fast reactors replace retired LWRs. The number of FRs that can be deployed in one year depends on both the number of retired LWRs and the available fissile material for FRs (i.e. reprocessing capacity). If not enough fissile material are available to replace a LWR with FR an ALWR is built. After all the existing LWRs are replaced with both ALWRs and FRs (around 2040), the fraction of deployed fast reactors reaches a value of about 21%. This fraction remains constant until about 2075 when it starts to grow again as ALWRs built in the 2020's are retired and are replaced with FRs. The FR fraction reaches a steady value again about 2090.

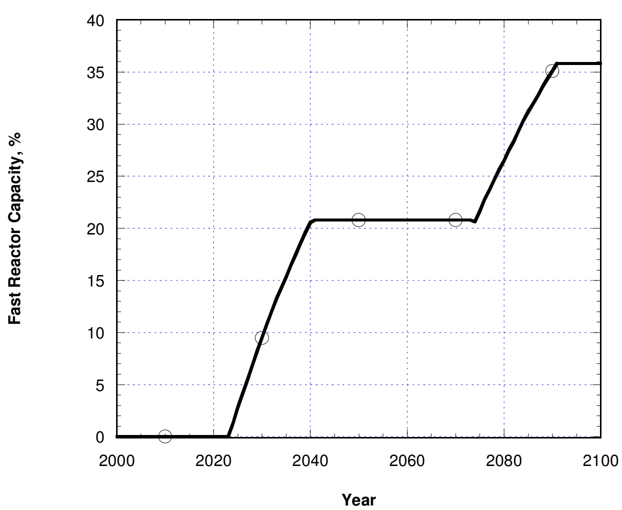

Fig. 3. Fast Reactor Transmuters Deployed Capacity Fractions for the No-Growth Scenario.

The FR fraction reached about the year 2040 shows an early limit on FR deployment while keeping the total nuclear capacity constant. This limit is dependent on both the reprocessing capacity and the timing of the deployment of this capacity. Figure 4 shows this early limit on FR deployment as a function of reprocessing capacity and timing of reprocessing capacity deployment. The first data point of the plot corresponds to the ~21% maximum capacity shown in Figure 3 that is reached the year 2040 given a reprocessing capacity of 2,000 MT/year deployed the year 2020. Increasing the deployed capacity in that year from 2,000 to 3,000 MT/yr increases the maximum FR deployed fraction to about 27%. This fraction can be increased to about 46% if the starting reprocessing capacity is 4,000 MT/yr. The figure also shows the effect of delaying to the year 2027 the extra reprocessing capacity (beyond the starting 2,000 MT/yr capacity in 2020). This delay decreases the possible maximum FR fraction as shown in the figure. Thus, delaying the deployment of an extra 2,000 MT/yr of reprocessing capacity from the year 2020 to the year 2027 leads to a decrease in the possible early deployment of FRs from a 46% share to about 38% share. This highlights the importance of the timing of the reprocessing capacity deployment in determining the possible deployment of FRs.

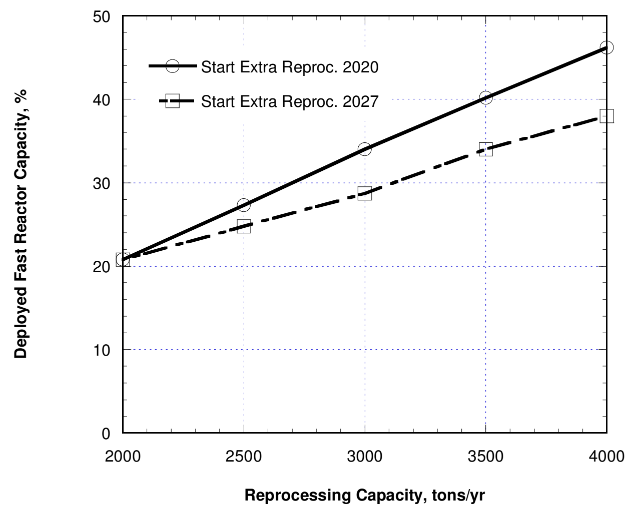

Fig. 4. Fast Reactor Transmuters Deployed Capacity Fractions as a Function of Reprocessing Capacity.

3.4 Impact of Recycle on Key Radioactive Species

Although recycling can reduce the mass of the SNF inventory, the inventory of key radioactive isotopes is much harder to reduce. Those key isotopes include the plutonium and neptunium, in addition to higher actinides. Figures 5 and 6 show the plutonium and neptunium (Pu + Np) inventories associated with the different scenarios for both no-growth and modest-growth cases, respectively. The amounts shown in the figure corresponds to the amounts included in the back-end of the fuel cycle and does not include the in-reactor inventories. The single MOX recycle can temporarily stabilize the Pu inventory until the MOX spent fuel accumulation leads to further increase in the Pu inventory. For this scenario, the minor actinide inventory increases steadily since only Pu is recycled.

This increasing trend in the Pu inventory can be reversed through the use of fast burner systems as shown in the figures. This is achieved at the cost of using significant capacity of the transmuter systems. The timing of the reversal in the Pu inventory trends is mainly dedicated by both power replacement and startup inventory requirements. As for modest growth scenarios, the inventory is roughly doubled for once-thru as shown in Figure 6, and it will be quite difficult to stabilize the Pu inventory as large processing and transmuter system capacity will be required.

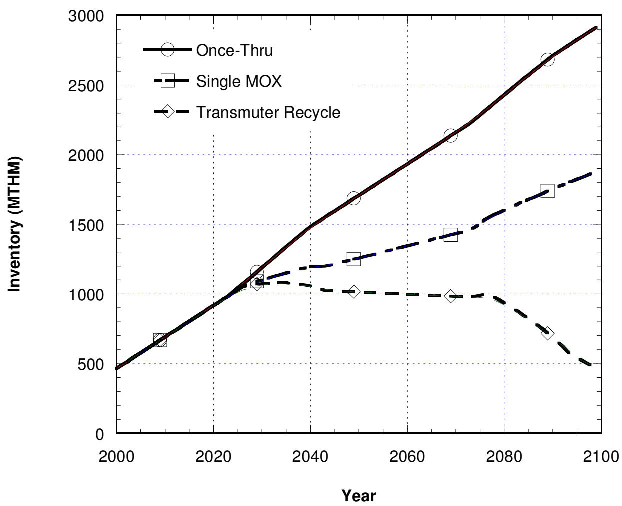

Fig. 5 Pu + Np Inventory for the Different No-Growth Scenarios.

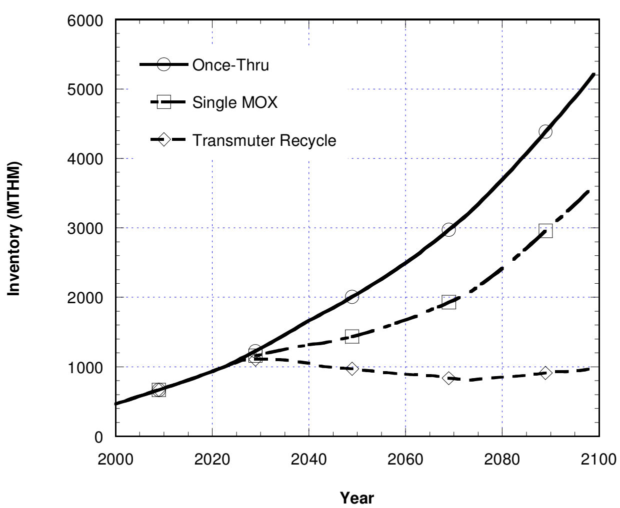

Fig. 6 Pu + Np Inventory for the Different Modest-Growth Scenarios.

It is important here to emphasis the fact that the inventories that were discussed here are those inventories in the back-end of the fuel cycle and does not include the in-pile inventories. Figure 7 shows the Pu+Np inventory destined to waste only. In the case of once-thru cycle, the entire Pu inventory is destined to waste. The single recycle in MOX delays the pile up of Pu inventory as part of that inventory resides in-pile. However the accumulation of the MOX spent fuel, which is considered as waste, ultimately leads to increase in the Pu inventory. Most of the Pu in the multi-recycle scenarios however remains in the processing stage or in-pile. In this case only reprocessing losses are destined for waste disposal.

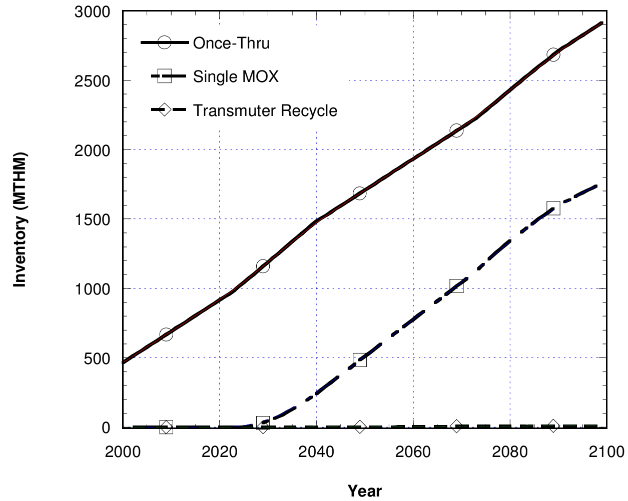

Fig. 7 Pu + Np Inventory to Waste for the Different No-Growth Scenarios.

3.5 Impact of Recycle on Repository

A wide variety of measures have been proposed to quantify and compare repository performance. Those measures include the radiotoxicity of disposed waste, dose rate from release at specified repository boundary and waste heat at a variety of cooling times (handling, storage). The waste loading in the current Yucaa mountain repository design is constrained by thermal limits. Thermal analyses have shown that the limit for direct disposal is the between-drift temperature which peaks ~ 1500 years after the waste emplacement [9].

The current work focused on decay power comparisons which are indicative of the impact of recycling on the repository capacity. The following is a discussion of the decay heat calculations employed in this work and the results for the different scenarios.

3.5.1 Decay Heat Calculations

An example of the decay heat calculations is shown in Figure 8. for LWR spent fuel discharge at 50,000 MWd/t burnup [10] (calculated using ORIGEN2 code [11]). In addition to the total decay heat generated , the figure shows the separate decay heat curves for U, Pu + Np, Cs + Sr, Am + higher actinides, and the remaining nuclides (others) as function of time after a 5-year post-irradiation cooling time (to 3,000 years). The total decay heat is shown as a function of time from time 0 after discharge to 3,000 years. The data shown in the figure are based on initial 1 MTHM.

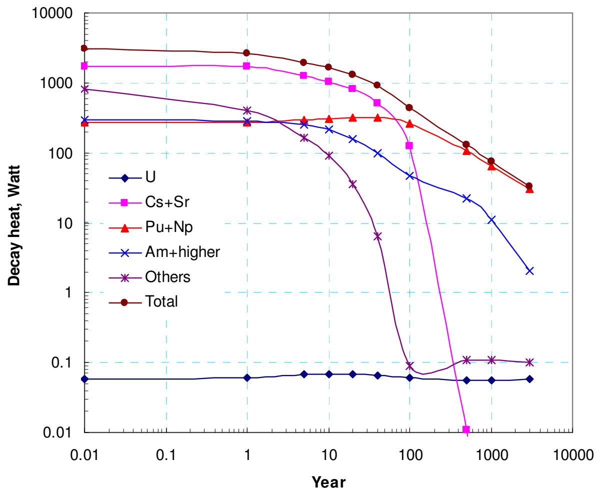

Fig. 8 Decay Heat for 50,000 MWd/t LWR Spent Fuel.

Based on those decay heat curves both short term and long term heat loads were estimated for the LWR spent fuel. The parameter that is considered in this study as a representative of the short term decay heat is the decay power at 100 years after placement into the repository (at the end of the repository ventilation period). Short-term decay powers for the different components of the LWR spent fuel are shown in Figure 9. The long-term heat load parameter considered here quantifies the cumulative amount of heat generated by spent fuel and/or high level waste (HLW) between about 100 years and 1500 years after the spent fuel had been discharged from the reactor.

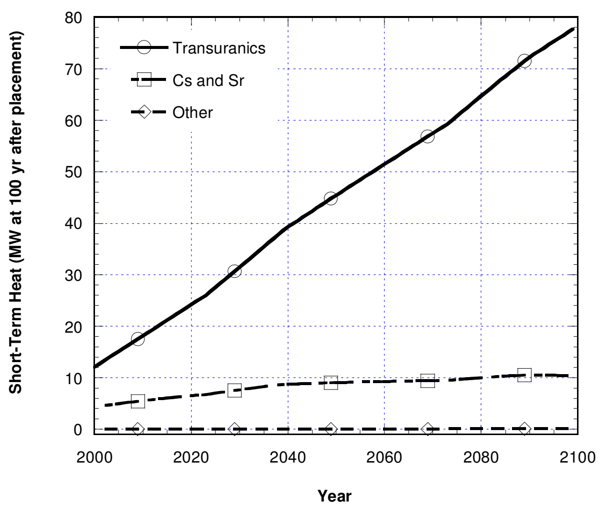

Fig. 9 Short-term Decay Power Contributions for LWR Spent Fuel Different Components.

The parameter is calculated by integrating the decay heat curves in Figure 8 between 100 and 1500 years. Again, 1500 years of decay heat was chosen based on the repository analysis which showed that the limits on repository capacity are based on the peak between-drift temperature that is reached ~1500 years after placement.

Those short-term and long-term decay heat parameters have been calculated for the different systems used in this study. The parameters are combined with the calculated masses of the different component of the waste stream to provide the decay heat associated with the different scenarios as described next.

3.5.2 Decay Heat for the Different Scenarios

Figure 10 shows the calculated long-term heat load in repository associated with the different scenarios (long-term integrated heat from 100-1500 years). The corresponding short-term decay power in the repository is shown in Figure 11 (short-term decay power at 100 years after placement).

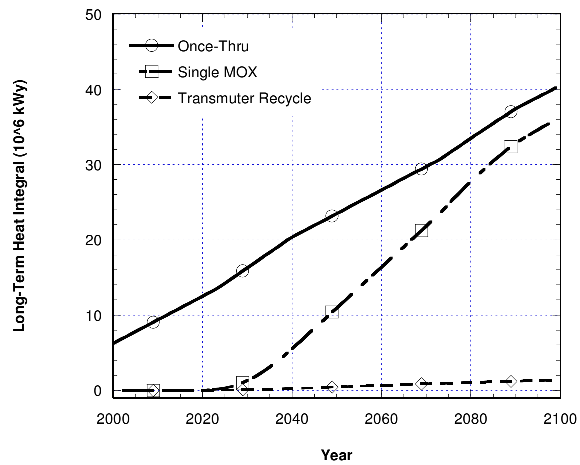

Fig. 10 Long-term Heat Load in Repository.

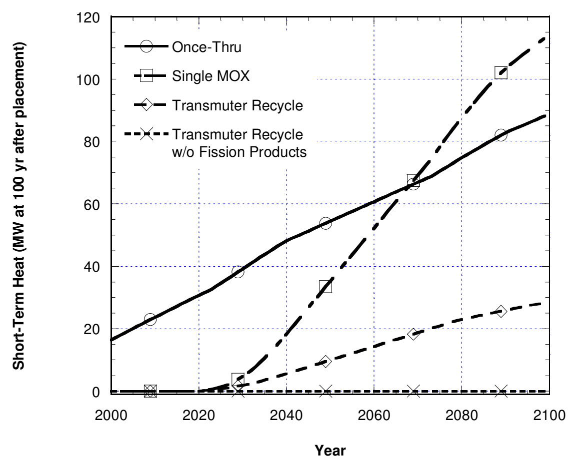

Fig. 11. Short-Term Decay Power in Repository.

Figure 9 shows the plutonium and minor actinides as the dominating short-term heat load compared to fission products, in addition to its dominance over the long-term heat load. As shown in Figures 10 and 11, the removal of most of the Pu and minor actinides from the waste destined to repository (the case of transmuter recycle) greatly reduces both short and long term decay heat. This can have the potential of reducing the needed repository space (for repository where thermal temperature constraints exist). However, in this case fission products become important in determining the size of repository.

Further removal of fission products (Cs + Sr) from that waste can significantly improve its short-term decay power as shown in Figure 11, leading to possible further reduction in the repository size. This shows the importance of the Cs+Sr contribution to the post-closure (100 y after placement) heat load. That is in addition to the importance of the heat and dose from those fission products (e.g., Cs and Sr) to the handling period before repository closure.

MOX recycle only delays TRU waste, but does not eliminate it, and the long-term decay heat from the MOX eventually matches the decay heat from once-thru system as shown in Figure 10. The MOX short term decay power can be even higher than that from once-thru because of Pu-238 buildup, associated with the presence of Np-237 in the MOX spent fuel (Figure 11).

4. CONCLUSIONS

With extended nuclear power production, large inventories of spent nuclear fuel must be managed which are many times the proposed capacity of current repository designs. Fuel reprocessing can significantly reduce this inventory (mass reduction) and a processing infrastructure of at least current spent fuel discharge rate (2,000 MT/yr) will be required. In order to reduce the inventory of key species (e.g., plutonium) transmutation systems will be required.

A key result of this study is that exclusion of the transuranics (TRU) from the waste through recycling benefits the repository thermal criteria. The Pu and minor actinides dominate the short-term heat, long term heat, and repository dose and its removal is key to improving the geological disposal performance.

Also noted is that the MOX recycle only delays the heat load consequences, but does not eliminate it. Only multi-recycling that includes advanced thermal or fast transmutation system will achieve a significant reduction in the waste heat.

Finally, general findings based on the current study show that the original AFCI goal of reducing the inventory of the spent fuel and key waste species is difficult to achieve while improving the key repository performance parameters can be achieved.

ACKNOWLEDGMENTS

The authors would like to thank T. A. Taiwo, T. K. Kim, and J. A. Stillman for providing the decay heat data. This work was supported by the United States Department of Energy under Contract W-31-109-ENG-38, and the DOE Advanced Fuel Cycle Initiative.

REFERENCES

1. Report to Congress on Advanced Fuel Cycle Initiative: “The Future Path for Advanced Spent Fuel Treatment and Transmutation Research,” U. S. Department of Energy, Office of Nuclear Energy, Science, and Technology, January 2003.
2. R. N. Hill, et al., “Multiple Tier Fuel Cycle Studies for Waste Transmutation,” *Proc. ICONE 10*, April 14-18, 2002, Arlington, VA, USA.
3. US-DOE Energy Information Administration, http://eia.doe.gov/.
4. US-Department of Energy, “A Technology Roadmap for Generation IV Nuclear Energy Systems,” GIF-002-00, Dec. 2002.
5. L. Van Den Durpel, A. Yacout, D. Wade, H. Khalil, “DANESS, Dynamic Analysis of Nuclear System Strategies,” *in GLOBAL 2003 Meeting*, November 16-20, 2003, New Orleans, LA, USA.
6. C. G. Bathke, et. al., “NFCSim: A Dynamic Simulation Model of the Nuclear Economy,” in Advances in Nuclear Fuel Management III (ANFM 2003).
7. M. A. Smith, E. E. Morris and R. N. Hill, “Physics and Safety Studies of Low Conversion Ratio Sodium Cooled Fast Reactors,” *Nuclear Technology: Achieving Global Economic Growth While Safeguarding the Environment*, New Orleans, LA, Nov. 16-20, 2003, American Nuclear Society.
8. L. Van Den Durpel, D. C. Wade, H. Khalil, A. Yacout, “Dynamic Analysis of Nuclear Energy System Strategies for Electricity and Hydrogen Production in the USA,” *in GLOBAL 2003 Meeting*, November 16-20, 2003, New Orleans, LA, USA.
9. R. Wigeland, T. Bauer, T. Fanning, E. Morris, *Repository Impact of LWR MOX and Fast Reactor Recycling Options*, ANS Winter Meeting / Global 2003, New Orleans, November 16-20.
10. T. K. Kim, Private Communications, July 2003.
11. A. G. Croff, “ORIGEN2- A Revised and Updated Version of the Oak Ridge Isotope Generation and Depletion Code,” Oak Ridge National Laboratory, ORNL-5621.